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REVERSE MONTE CARLO SIMULATIONS OF MICROWAVE RADIATIVE TRANSFER IN REALISTIC 3-D RAIN CLOUDS

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1 INTRODUCTION

For the most effective utilization of satellite microwave radiometry to estimate precipitation parameters, it is essential for algorithm developers to have the best possible understanding of the physical relationship between precipitation and microwave radiances. This includes the ability not only to quantify this relationship under highly idealized conditions (e.g., plane-parallel, Marshall-Palmer distributed Mie spheres) but also to accurately assess the role of real-world deviations from the ideal.

To date, the principal tool for studying microwave radiative transfer in the atmosphere has been any of a number of plane-parallel radiative transfer codes. Consequently, the role of the three-dimensional structure of rain clouds has received comparatively little theoretical attention to date.

With the greatly increased power of current-generation computer workstations it is finally practical to model and study the microwave signature of precipitation in considerably greater detail. In particular, the traditionally prohibitive computational demands of Monte Carlo models — which remain the only models capable of handling completely arbitrary geometries and scattering properties — has ceased to be a major obstacle to their routine use. This is especially the case for the Reverse (a.k.a. Backwards or Adjoint) Monte Carlo method of simulating of satellite-observed radiances, since computation is expended only on those photons actually arriving at the sensor.

A Reverse Monte Carlo technique was apparently first applied to the problem of microwave radiative transfer in precipitation by Petty (1994), who simulated SSM/I radiances from idealized cuboidal rain clouds. Among other things, that study confirmed that the so-called beam-filling bias is very sensitive to three-dimensional cloud geometry, owing to the prominent role of emission from the sides of clouds and from surface reflections in determining the scene-averaged brightness temperature. Nevertheless, the above results were based on highly simplified geometries and microphysical properties and were presented primarily for their illustrative or heuristic value rather than for the purpose of deriving accurate relationships between rain parameters and brightness temperature.

The purpose of this paper is to document certain improvements in the Reverse Monte Carlo model under development at Purdue University and to demonstrate its application to realistic hydrometeor distributions generated by a 3-D numerical cloud model.

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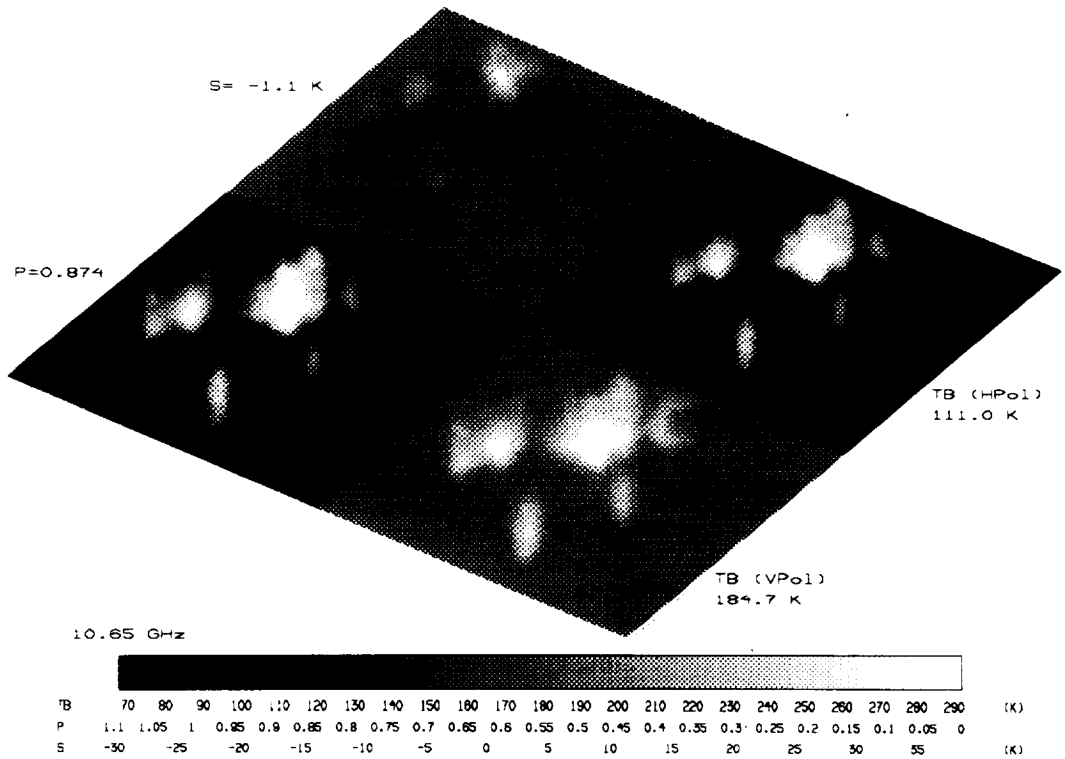

Fig. 1: Simulated perspective view of a convective cloud system at 10.7 GHz and at time 0340 of the model simulation. The maximum surface rain rate at this time was approximately 20 mm hr^{-1}. Bottom and right panels depict vertically and horizontally polarized brightness temperatures, respectively. Left and upper panels depict the transformed P and S indices defined by Petty (1994). Values printed on the margins of each panel indicate domain averages. Domain size is 51 km.

2 MONTE CARLO MODEL

While space does not permit a detailed description of the model here, the Purdue Monte Carlo model operates on arbitrary three-dimensional grids of the relevant optical parameters, which normally include volume extinction coefficient k_{ext}, single scatter albedo ϖ, asymmetry factor g, and thermodynamic temperature T. Simulated photons are traced in a time-reversed sense from the direction of the sensor into the cloud domain, where absorption events may be equated, by virtue of Kirchhoff's Law, with radiant emission seen by the satellite.

By releasing a suitable number of photons from every gridpoint in the $x - y$ plane at the top of the model domain and by projecting the resulting image in the viewing direction, the model produces a true-perspective oblique view of the three-dimensional structures occupying the domain. One may therefore for the first time "see" precipitating cloud structures exactly as they might appear to a microwave imager with "infinite" (i.e., $\lesssim$ 1 km) spatial resolution.

3 CLOUD MODEL AND RADIATIVE PARAMETERIZATIONS

For the purpose of demonstrating the capabilities of the Reverse Monte Carlo approach and of illustrating the microwave properties of realistic 3-dimensional rain clouds, we have applied the Purdue Monte Carlo code to the same COHMEX (Cooperative Huntsville Meteorological Experiment) hail storm simulation results that served as the basis for the microwave radiative transfer study by Smith et al. (1992).

The Colorado State University (CSU) cloud-mesoscale model results for COHMEX, and the conversion of hydrometeor fields to the microwave optical parameters required for radiative transfer calculations, have been documented extensively elsewhere (see Smith et al. 1992 and references therein). It is sufficient to note here that the model provides, among other things, 3-D fields of water vapor, cloud water, cloud ice, rain water, graupel, and snow aggregates at 1 km horizontal resolution and approximately 250 to 500 m vertical resolution. The optical

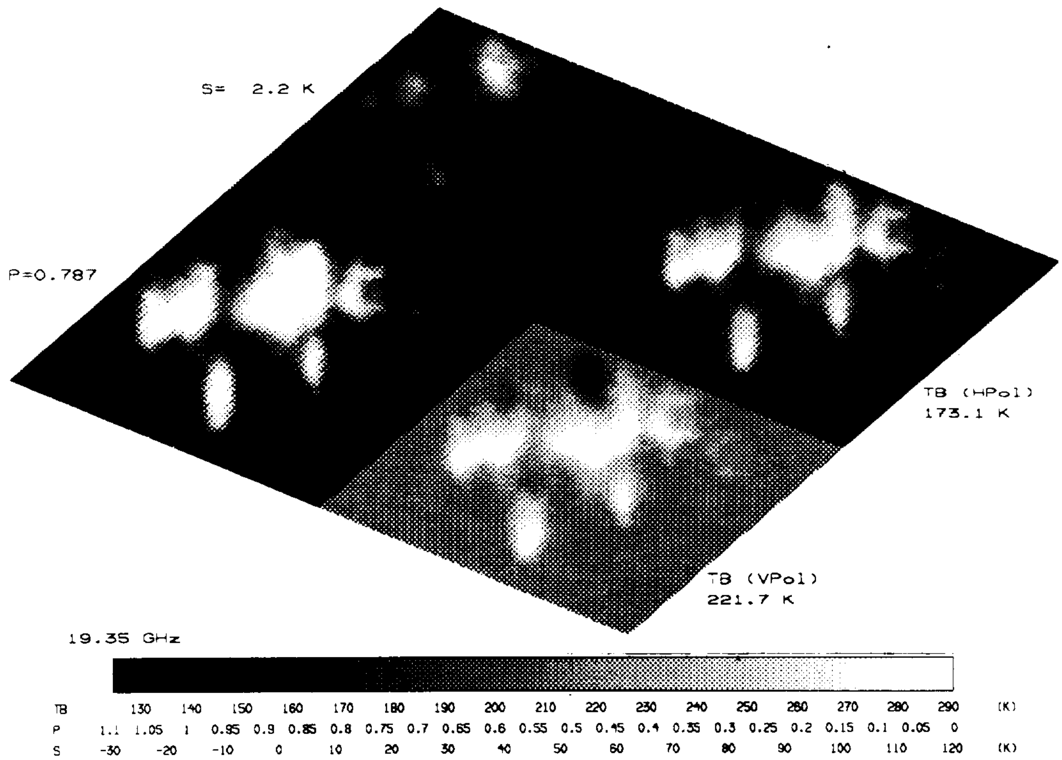

Fig. 2: Same as Fig. 1, but for 19.35 GHz.

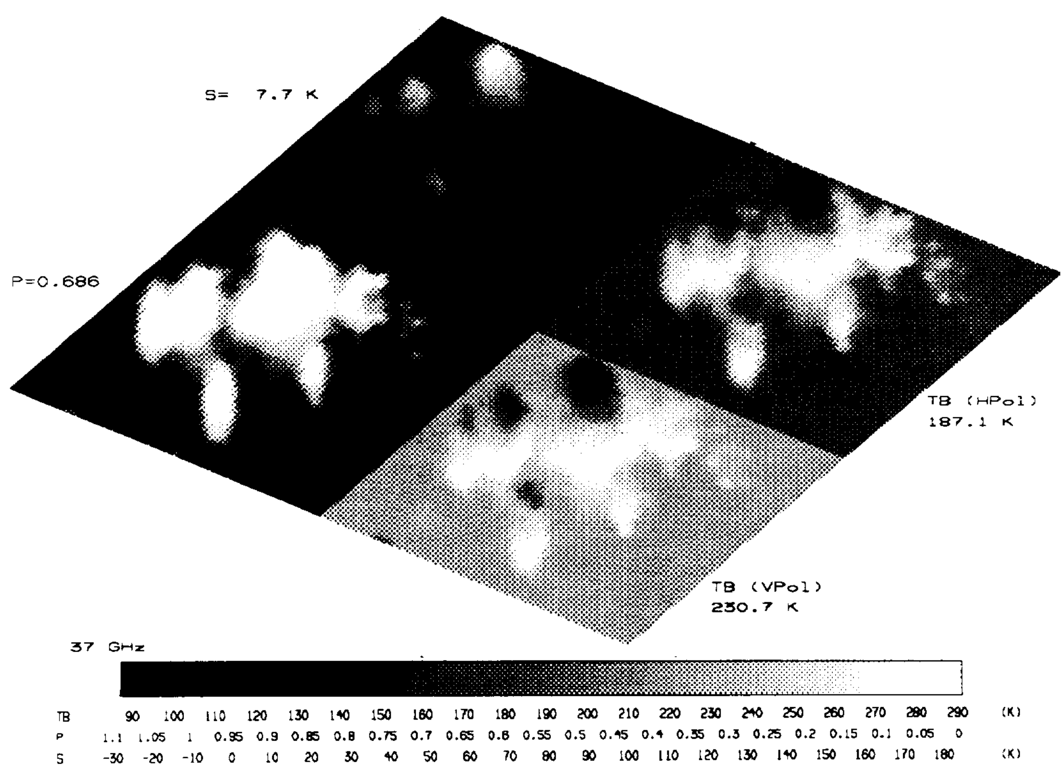

Fig. 3: Same as Fig. 1, but for 37.0 GHz.

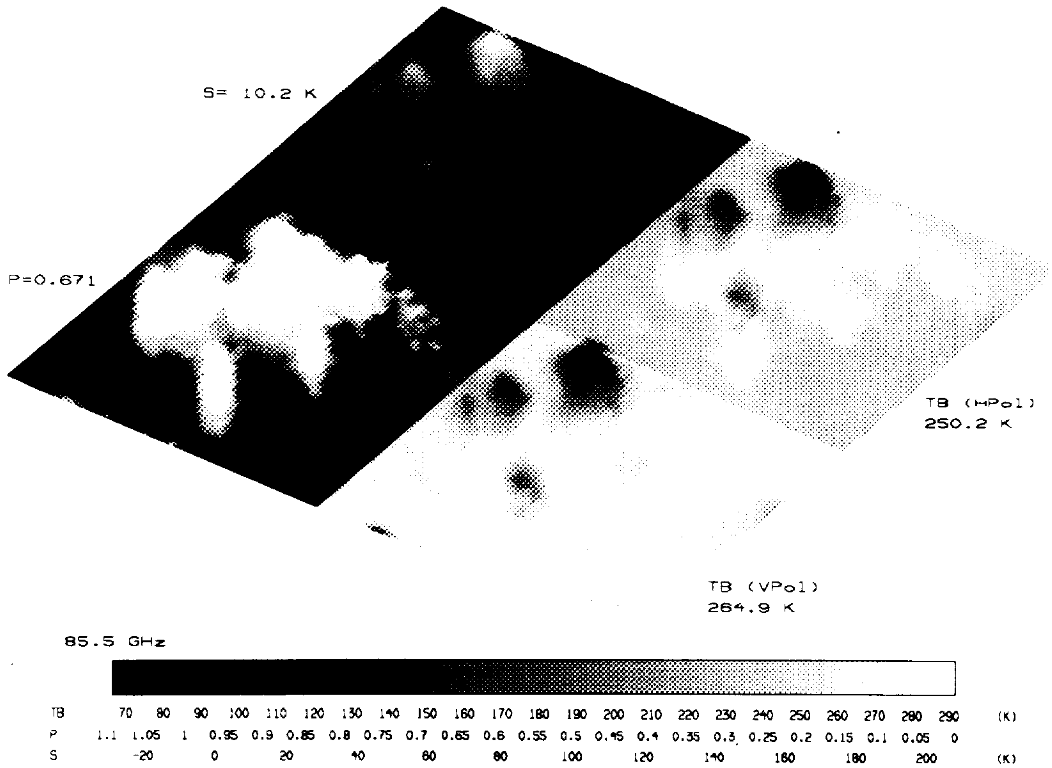

Fig. 4: Same as Fig. 1, but for 85.5 GHz.

properties of each of these constituents are parameterized and combined as described in Appendix B of Smith et al. (1992).

4 RESULTS

Figures 1–4 depict Monte Carlo simulations for time 0340 in the CSU model run. The columnar water equivalent for this time step may be found in Fig. 3 of Smith et al. (1992). Four commonly used frequencies — 10.7, 19.35, 37.0, and 85.5 GHz — are represented. Fresnel reflection for a seawater surface was assumed at the lower boundary.

Space does not permit a detailed discussion, but the following features may be noted:

(1) For all channels, the ocean surface reflection of the rain clouds' emission greatly magnifies the apparent fractional coverage by the rainfall.

(2) In the untransformed brightness temperature images, there is generally a mixture of (a) strong emission from the sides of water clouds and their reflections and (b) significant brightness temperature depressions due to scattering by ice.

(3) The normalized polarization P and scattering index S transformations defined by Petty (1994) are able to effectively decouple the above two components.

(4) Even at 10.7 GHz, the S field reveals a concentrated pocket of pronounced scattering — presumably due to heavy graupel — within the most active storm cell.

Acknowledgments

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